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Magnetization dynamics of a single-domain magnet under a spin-polarized current with a tilted polarization

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Abstract

Magnetization dynamics for a single-domain magnet under a spin-polarized current with a tilted polarization was investigated by solving the Landau-Lifshitz-Gilbert-Slonczewski equation. Taking into consideration the uniaxial magnetic anisotropy, the stationary-state solutions of the magnetization vector could be analytically obtained by solving an algebraic cubic equation. It was found that one to three pairs of magnetic stationary-states existed, depending on the applied current density and the spin-polarized direction. The critical switching current and reversal time for magnetization switching were numerically found under different tilted polarization configurations with considering different forms of the spin-polarized function. The results may be useful for the design of the future spintronic devices.

Keywords: Spin transfer torque, magnetization switching, tilted spin polarization

1 Introduction

The high speed and low power consuming computer memories and data storage devices have been expected in the current days. One of key technologies realizing such devices is the manipulation of the magnetization of a nanomagnet by use of the spin transfer torque (STT). The idea of STT generated by a spin-polarized electric current was independently suggested by Slonczewski [1] and Berger [2] in 1996, and was verified by several experiments [3-5]. STT relies on a strong, short range interaction between a spin current and the background magnetization of a nanomagnet. Spin transfer induced magnetization switching therefore has important advantages over field induced switching and will likely form the basis for a new generation of magnetic information storage devices [6].

A conventional STT device named spin valve [1] is a triple layer structure which has a thick magnetic polarized layer, a nonmagnetic metal spacer and a thin magnetic free layer. The spin-

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polarized current flowed from the polarized layer, whose polarization direction vector is denoted by $\vec{s}$, acts a torque on the magnetization of the free layer whose magnetization direction vector is $\vec{m}$. The torque caused by the current is along the direction of the vector $\vec{m}\times(\vec{s}\times\vec{m})$. It fluctuates the magnetization or even reverses its direction when the current (density) exceeds a critical value. Important issues in its applications are to lower the critical current required to reverse a magnetization and to design a current pulse such that the magnetization can be switched fast from initial state to targeted state. Experiments and simulations showed that the magnetization switching is slow but has low critical switching current when the spin-polarized direction of the current is almost parallel (or antiparallel) to the magnetization of the free layer. When the spin polarization of the current is perpendicular to the free layer magnetization, the magnetization switching is fast but requires elaborated controllability of the shape of the current pulse [7-8]. In order to resolve the problems of these two configurations, the use of a polarized layer with tilted directional angles in spin polarization has also been demonstrated by several groups to improve the magnetic switching speed and reduce the switching current in the STT-MRAM devices with retaining thermal stabilities [9-16]. Not long ago, it has been shown that the tilted polarizer configuration may have significant advantages for high frequency microwave output with zero-field operation in STT-oscillator applications [17].

In this work, magnetization dynamics analysis of a single-domain nanomagnet under a spin-polarized current with arbitrary tilted angles in polarization was investigated by solving the Landau-Lifshitz-Gilbert-Slonczewski equation. The stationary-state solutions of the magnetization vectors were analytically obtained and one to three pairs of magnetic stationary-states were found for uniaxial magnetic anisotropy, depending on the current intensity and the tilted angles in polarization. The macrospin simulation showed that how the critical switching current and magnetization reversal time change with the varying tilted angles. Also, results were obtained in the simulations under two different situations where considering the Slonczewski's spin-polarized g-function type or not, which may imply that the interaction between spin-polarized electrons and the free layer magnetization do not always promote magnetization switching.

2 Model

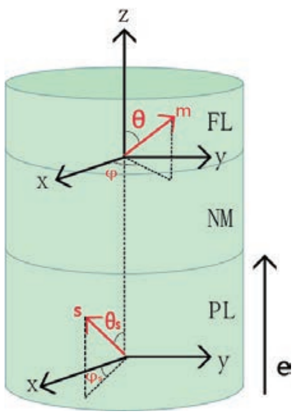

Figure 1: (Color online) A schematic diagram of a spin valve in the tilted polarization configuration and the corresponding coordinate system. PL, NM, FL denote the polarized layer, nonmagnetic metal layer and the free layer, respectively. The *s*-vector denotes the spin-polarized direction and the *m*-vector denotes the magnetization vector in the free layer. The letter e denotes the direction of the electron flow.

The considering spin valve is a magnetic multi-layers structure, which consists of a free layer and a tilted polarized layer separated by a nonmagnetic layer, as shown in Fig.1. $\vec{m}$ is the unit vector of the free layer magnetization, which was modeled as a Stoner-Wohlfarth magnet [18-21] under a spin-polarized current through spin transfer mechanism. The polarized layer should be chosen much thicker than the free layer so that the former's tilted polarization direction (denoted by $\vec{s}$ -vector), which could be generated and pinned by such as a localized magnetic field, is approximately unchanged. When electrons flow from the tilted polarized layer into the free layer, most of their spins will be polarized along the polarized layer's magnetization direction (the *s*-vector in Fig.1). The spin-transfer torque (STT) is in a direction given by $\vec{m}\times(\vec{s}\times\vec{m})$, which will act on the magnetization of the free layer and cause it to rotate out of plane. Theoretical studies [1] showed that the STT $\vec{\Gamma}$ is proportional to the current with the following form,

$$\vec{\Gamma} = \left[\frac{d(\vec{M}V)}{dt}\right]_{STT} = a_I \vec{m}\times(\vec{s}\times\vec{m}),$$

where $a_I = \frac{\gamma\hbar I}{\mu_0 e M_s V}\cdot g(P,\vec{m}\cdot\vec{s})$ denotes the torque strength, and V, $\hbar$, μ_0, and e denote the volume of the free layer, the Planck constant, the vacuum magnetic permeability, and the electron charge, respectively. $\vec{M}$ is the total magnetization vector of the free layer, $\vec{M} = M_S\vec{m}$. Here I is the current density, M_S is the saturation magnetization, and $\gamma = 2.21\times10^5 (rad\cdot m/A\cdot s)$ is the gyromagnetic ratio. The g-function,

$$g(P,\vec{m}\cdot\vec{s}) = \frac{4P^{3/2}}{(1+P)^3(3+\vec{m}\cdot\vec{s})-16P^{3/2}},$$

is now referred to as the Slonczewski's spin-polarized function [1], where P is spin polarization ratio of the current. Experimental investigations so far [3-5] were qualitatively consistent with this polarization function, which will be used in our following study. For a comparison, we also employed $a_I = \frac{\gamma\hbar I}{2\mu_0 e M_s V}\cdot P$ in our study as a simplified STT form, where P replaces the g-function simply.

The Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation for the free layer magnetization dynamics including a spin current induced torque predicted by Slonczewski is,

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_t + \alpha\vec{m}\times\frac{d\vec{M}}{dt} - \gamma a_I\vec{M}\times(\vec{m}\times\vec{s}), \qquad (1)$$

where α is a phenomenological dimensionless damping constant whose typical value ranges from 0.01 to 0.22 for Co films. $\vec{H}_t$ is the effective magnetic field including the applied external field and the anisotropy field and so on. In this work, we consider the situation with no applied external field but an anisotropic field. The uniaxial magnetic anisotropy is $\omega(\vec{m})=-km_z^2$ with its easy axis along the *z*-direction. Let $\vec{e}_r,\vec{e}_\theta,\vec{e}_\varphi$ be the three unit vectors in spherical coordinates. In terms of θ and φ, Eq.(1) can be written as,

$$(1+\alpha^2)\dot{\theta} = h_{t,\varphi} + \alpha h_{t,\theta} - a_I(\alpha s_\varphi - s_\theta),$$

$$(1+\alpha^2)\sin\theta\dot{\varphi} = \alpha h_{t,\varphi} - h_{t,\theta} + a_I(\alpha s_\theta - s_\varphi),$$

where $s_\theta = \sin\theta_s \cos\theta \cos\Delta\varphi - \cos\theta_s \sin\theta$, $s_\varphi = \sin\theta_S \sin\Delta\varphi$, and $\Delta\varphi = \varphi_S - \varphi$. Here, the unit vector in spin-polarized direction with an arbitrary angle in the polarized layer can be described by: $\vec{s} = (\sin\theta_S \cos\varphi_S, \sin\theta_S \sin\varphi_S, \cos\theta_S)$, and the unit magnetization vector in the free layer can be described by: $\vec{m} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$, where $0<\theta_S,\theta<\pi$ and $0<\varphi_S,\varphi<2\pi$. θ and θ_S are the polar angles for $\vec{m}$ and $\vec{s}$, respectively, while φ and φ_S are the azimuth angles for the *z*-axis (the easy-axis) as shown in Fig.1. For the uniaxial anisotropic model we can let $\varphi_S = 0$.

According to the Eq.(1), the critical switching current and the reversal time at the same applied current density for the magnetization reversal in the free layer can be numerically calculated under different tilted polarization configurations with considering the Slonczewski's polarization g-function or not. In the following simulations, the material parameters of an ultrathin Co film were employed with the saturation magnetization $M_S = 1.5 \times 10^6 A/m$ and the damping $\alpha = 0.1$. The effective magnetic anisotropic energy that is perpendicular to the film plane depends on the Co film thickness and the matching condition between the adjacent multilayer [22]. It was assumed that the thickness of the Co film was 1nm and $K \approx 3.1 \times 10^5 J/m^3$, taken from Ref.[22]. Thus, the dimensionless uniaxial anisotropic constant was $k = K / (\mu_0 M_S^2) \approx 0.11$.

3 Results

According to the previous analysis [16], the stationary-state solutions of the magnetization vector under any tilted polarization configurations can be analytically obtained by solving an algebraic cubic equation, $Bx^3 - Bx^2 + (1+A)x - A = 0$, where $x = \cos^2\theta \in [0,1]$, $A = \cot^2\theta_S$, $B = [2/(d\sin\theta_S)]^2$ ($d = a_I / k$ denotes the dimensionless current density strength). By analyzing the discriminant of the cubic equation, $\Delta = N^2 - M^3$, where $M = 1/9 - d^2/12$, $N = d^2(3\cos^2\theta_S - 1)/24 + 1/27$, one to three pairs of stationary-state solutions of the magnetization vector can be analytically found. In Fig.2, we plotted the phase diagram of the number of magnetic stationary-states with a dependence on the dimensionless current density strength *d* and spin polarization angle θ_S. The solid (blue) curve shows the discriminant $\Delta = 0$. Thus, among the triangle-shaped area enclosed by the curve (marked as A area) where $\Delta < 0$, there exist three pairs of stationary-state solutions of the magnetization. That is to say, the magnetization vector $\vec{m}$ would be along one of the six different directions for the current configuration parameters (d, θ_S) within this regime after a long period of time. While outside the curve (marked as B area) where $\Delta > 0$, there exists only two stationary-state solutions of $\vec{m}$. The magnetization would likely to be along one of the two directions finally.

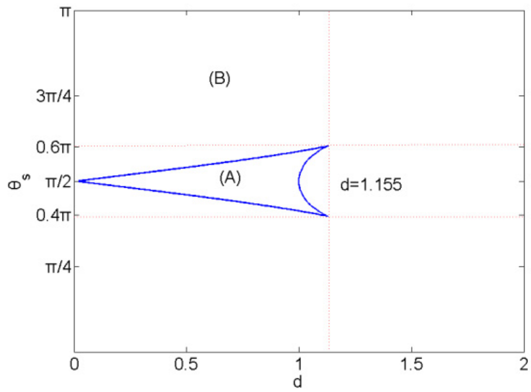

Figure 2: (Color online) A phase diagram of the magnetization stationary-state solution numbers with the dependence on the dimensionless current strength $d = a_I / k$ and the current spin polarization angle θ_S. Among the triangle-like area (A) there are three pairs of stationary-state solutions, while in area (B) there is only one pair of stationary-state solutions.

The magnetization switching time t_f of a single-domain nanomagnet is defined as the period for the magnetization vector switched from the initial state ($\theta = 0$) to the targeted state ($\theta = \pi$). In usual it decreases monotonously with the increment of the applied magnetic field and current density, or the stress induced from an electric field on a magnetostrictive nanomagnet [23,24]. In our numerical simulation, we have focused on how the magnetization switching time changes with the varying tilted angles of spin polarization. A non-monotonic switching time dependence on the tilted angles was found in two different situations where the Slonczewski's spin polarized g-function was considered or not. As shown in Fig.3, by applying a current at 5μA on the spin valve, the magnetization switching time has been found to have an order of 0.1ns at most of the tilted angle configurations for a Co magnet with a volume of 1nm^3. When the tilted angle θ_s is greater than 0.639π (the intersection point between two lines in Fig.3), the switching time is lower at the situation of considering the Slonczewski's g-function (the dotted blue line). While for θ_s smaller than 0.639π, the switching time is lower when the spin-polarized function is considered simply proportional to the polarization ratio P (the solid green line). Thus, the concrete forms of polarized functions, which imply the detailed spin interaction between the ferromagnetic layers and the iterant electrons, may be important for magnetic switching. Besides, when the tilted angle approaches 0.5π (referred as the usual *perpendicular* configuration) or π (usual *parallel* configuration), the switching time increases rapidly, which is due to the inefficiency of the spin transfer at both configurations.

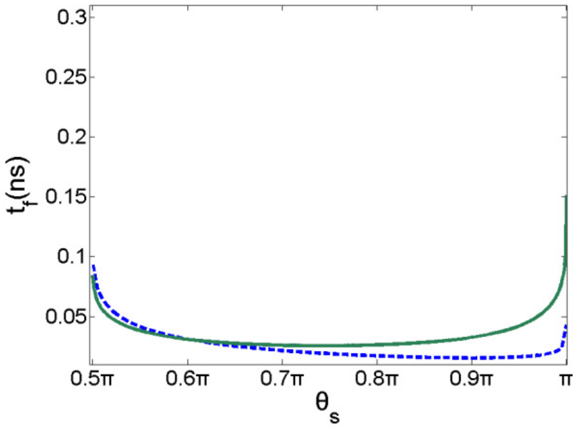

Figure 3: (Color online) The magnetization switching time t_f versus the spin polarization tilted angle θ_s. The dotted (blue) line denotes the situation considering the Slonczewski's spin-polarized g-function, and the solid (green) line is for the situation that the polarization function is simply proportional to the polarized ratio *P*.

The critical switching current I_c was also found numerically for different tilted polarization angles in two situations considering the Slonczewski's polarized g-function or not. As shown in Fig.4, the critical switching current was found of the order of 1μA for a Co magnet with 1nm^3. I_c decreased monotonously as θ_s increased from 0.5π to π. When the tilted angle θ_s is between 0.585π and 0.69π (the two intersection points between two lines in Fig.4), the critical current is higher at the situation when considering the Slonczewski's polarized g-function (the dotted blue line), while for other angles the critical switching current is lower when the spin-polarized function is simplified as o the polarization ratio *P* (the solid green line). In particular when θ_s approaches π (parallel configuration), the critical current will approach to minimal values for considering the Slonczewski's g-function. It implies that an appropriate form of the spin-polarized function may lower the critical current and switching time simultaneously under larger tilted angle configurations (greater than 0.9π).

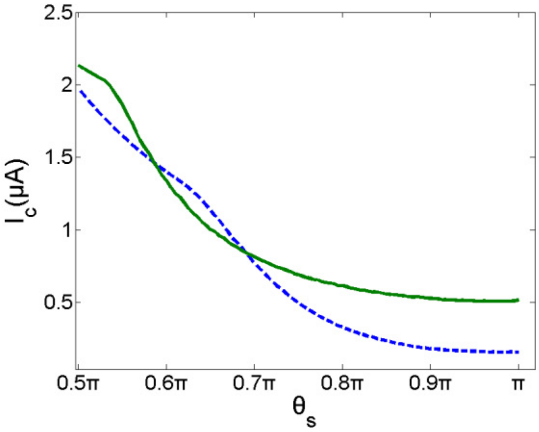

Figure 4: (Color online) The critical switching current I_c for the magnetization switching versus the tilted angle θ_s. The dotted (blue) line denotes the situation considering the Slonczewski's spin-polarized g-function, and the solid (green) line is for the situation that the polarization function is simply proportional to the polarization ratio P.

4 Conclusion

To conclude, on the basis of the LLGS equation, we numerically studied the spin-torque induced magnetization switching in the spin valve under a spin-polarized current with tilted polarization angles. Two similar with a little different results about the relationship between the magnetization switching time t_f, the critical switching current I_c and the tilted angle θ_s were obtained with considering different forms of polarized function types. The simulations showed that the critical current for magnetization switching is monotonously decreasing with increasing the tilted angle and the magnetization reversal time has a minimum value for varying the tilted angles, neither in parallel nor in perpendicular configuration. The results of the critical switching current suggested that considering the Slonczewski's spin-polarized g-function would not lower the critical current value in the entire tilted angle regime than the case of simply considering the polarization P-factor type. It indicates that the interaction between spin-polarized electrons and the free layer magnetization do not always promote magnetization switching. This work may be useful for designing the future STT devices.

Acknowledgments

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